The HERO Program, high-energy replicated optics for a hard-x-ray balloon payload

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ABSTRACT

We are developing high-energy replicated optics for a balloon-borne hard-x-ray telescope. When completed, the telescope will have around 130 cm ^{2} of effective collecting area at 60 keV, and an angular resolution of ⦸ 30 arc seconds, half power diameter. With an array of gas scintillation proportional counters in the focal plane the payload will provide unprecedented sensitivity for pointed observations in the hard-x-ray band. We present an overview of the *HERO* program, together with test data from the first mirror shell. The overall sensitivity of the full payload is given for planned long- and ultra-long-duration balloon flights.

Keywords : X ray, telescope, optics, replicated, balloon.

1. INTRODUCTION

The impact of focusing optics in x-ray astronomy has been enormous. The *Chandra* telescope has approximately the same collecting area as the detectors on the first satellite devoted to x-ray astronomy, *Uhuru*, yet will have 5 orders of magnitude more sensitivity. Accomplishing similar advances at higher energies, in a relatively unexplored energy regime, awaits the development of suitable optics.

We believe that shallow-graze-angle replicated mirrors, as currently utilized at low energies, are also the best approach for achieving useful, high-resolution, hard-x-ray optics. We first pointed out that achieving decent response at hard-x-ray energies does not necessarily involve use of a graded-multilayer[1]. The reason is simple: The effective area of any reflecting x-ray optic scales as α^2R^2, where R is the reflectivity and α is the mean graze angle. Comparing the reflectance of conventionally-coated mirrors (about 0.9) with those currently being developed for hard-x-ray use, namely multilayer-coated foil mirrors (typically 0.4)[2], we see that an equivalent effective area conventional optic is 2.25-times smaller in diameter, thus requiring an optic that is easier to build, albeit at half the field of view for the same focal length. Further, and perhaps even more important, diffractive scattering by surface micro-roughness *increases* with graze angle. Ultimately, scattering is the dominant contribution to the half-power diameter, and is less in shallow-graze-angle optics than in larger-angle multilayer-coated optics. Thus, realistic side-by-side comparisons show that "conventional" optics are more suited for high-angular-resolution hard-x-ray astronomy. Further, the higher angular resolution afforded by the replication process translates directly into improved sensitivity for a given collecting area.

To demonstrate the viability of this approach we initiated the High Energy Replicated Optic (*HERO*) program detailed below. *HERO* will provide a balloon-borne payload capable of sub-mCrab sensitivity up to 70 keV and with an angular resolution around 30 arc sec.

2. BALLOON PAYLOAD

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The *HERO* mirror payload consists of 16 identical 6-m-focal-length mirror modules, each containing a nested array of 12 mirror shells of diameters ranging from 50 to 70 mm. Each shell has a segment length of 305 mm (610 mm total, one piece), is a conic approximation to a Wolter-1 geometry, and is an electroformed nickel alloy, 0.25-mm thick. The resulting graze angles range from 3.5 to 5 arc min and, when the shells are coated with iridium, gives each module useful response to about 75 keV. A surface finish of 6 Å rms (based on Wyko metrology of the mandrel above ~ 3 mm^{-1}) and the sub-micron figure accuracy, achieved on our first 'optical quality' mandrel, gave an angular resolution of about 30 arc sec half power diameter (see below), dominated by axial slope errors. We plan to improve on this with future mandrels currently under fabrication and note that the contribution of the conic approximation (to the Wolter-1 geometry) to the overall HPD is only 5 arc sec. Table 1 details the *HERO* payload mirror configuration.

Table 1: *HERO* balloon payload mirror configuration

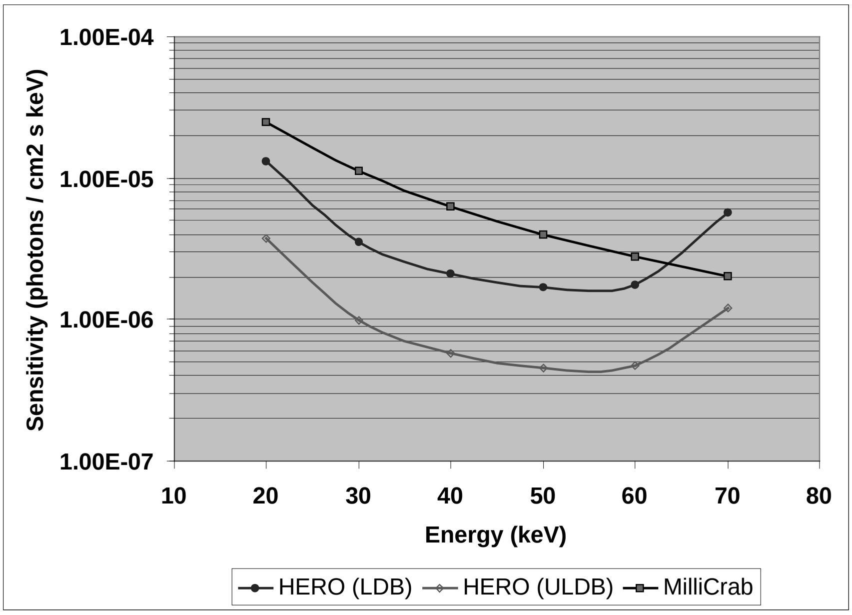
Mirror shells per module	12
Inner shell diameter	50 mm
Outer shell diameter	70 mm
Total shell length	610 mm
Focal length	6 m
Type	Conic approximation to Wolter 1
Fabrication process	Electroformed nickel replication
Shell thickness	0.25 mm
Coating	Sputtered iridium
Number of mirror modules	16
Effective area	~ 130 cm^2 at 60 keV
Angular resolution	30 arc sec to 60 keV
Sensitivity at balloon float altitude (3 g / cm^2) 5σ in a 10 keV band.	2.10^{-6} photons / cm^2 s keV at 60 keV (10^5 s) 5.10^{-7} photons/ cm^2 s keV at 60 keV (10^6 s)

For the *HERO* focal plane, we are developing Gas Scintillation Proportional Counters (GSPC). These are well developed for low-energy-imaging applications and their extension to high energies is a relatively simple matter of increasing the fill-gas pressure. Our work on the GSPC is covered in a separate paper in this conference [3]. We are also evaluating cadmium-zinc-telluride pixellated detectors for possible future focal plane use [4].

Long-Duration Balloon (LDB) and future Ultra-Long-Duration Balloon (ULDB) flights provide ideal opportunities for high-sensitivity, hard-x-ray imaging with this telescope. We plan to fly the payload on our refurbished HCO/CfA/MSFC gondola, modified to accommodate the 6-m focal length. Work is progressing at MSFC and includes a re-designed pointing system and a novel day/night aspect star camera [5]. Our collaborators at HCO/CfA are providing additional gondola modifications (telemetry and power) for LDB operation.

When the mirror payload is coupled with the GSPC focal plane detectors, for which we have used a net background of 10^{-3} photons / cm^2 s keV at 30 keV and 5.10^{-4} at 40 keV, we anticipate the sensitivities depicted in Figure 1, assuming 30-arc-sec optics. The sensitivity of this payload is such that over a thousand galactic sources will be available for exploration in a 10-day long-duration balloon flight compared to the tens of sources that are currently accessible on 1 to 2 day flights with non-focusing instruments. The great power of focusing optics, even with relatively modest collecting areas, is immediately apparent; On ultra-long-duration flights the *HERO* payload will obtain 100-µCrab sensitivity.

Figure 1: *HERO* balloon payload 5-σ sensitivity in each of 5 independent 10-keV bands for a 10^5 s (LDB)



and 10^6 s (ULDB) observation.

3. MIRROR DEVELOPMENT PROGRAM

3.1 Mirror Fabrication

The general approach that we have taken for mirror fabrication is that of electroform nickel replication off the surface of super-polished, aluminum mandrels. This process was pioneered in Italy [6], has already been used extensively for the mirrors on the XMM mission [7] and has been heavily developed at MSFC to satisfy the future needs for large-area light-weight high-resolution optics.

For hard-x-ray replicated optics we have had to develop additional specialized infrastructure. The aspect ratio of the shells has necessitated a production path that differs somewhat from that for the low-energy shells that MSFC has been developing. Rather than use diamond turning, we first grind the mandrels to figure, with a finish of around 0.1 micron rms, and then transfer to a purpose-built polishing machine for intermediate and final finishing. Periodically, the mandrel is removed from the polishing machine for metrology. Figure 2 shows a hard-x-ray mandrel on our long-trace profilometer. Once the performance prediction from the mandrel metrology is acceptable, the mandrel is treated to reduce adhesion (and thus permit the shell to be removed later without damage), and a shell is electroformed. This is done using a special low-stress process developed at MSFC. The resulting deposit is an ultra-low-ductility high-strength 'glassy' metal, an alloy of nickel that behaves mechanically more like a ceramic. The very high microyield strength of this material ensures that even very-large-diameter thin shells will not plastically deform during fabrication and handling. The use here, albeit for relatively small-diameter mirrors, serves as a test of the process for future large-area applications.

Once the mirror shell has been electroformed the mandrel plus attached shell is maintained at 45 °C, the temperature of the plating bath, and transported for separation. Separation is accomplished by making use of the large difference in thermal expansion coefficient between the aluminum mandrel and the electroformed nickel shell. A controlled shell release is achieved using a purpose-built separation fixture (Figure 3), which cools the assembly in a dry nitrogen environment and then guides the free shell over the small end of the mandrel. The mirror shell can then be coated with iridium in a dedicated sputtering system designed specifically for the *HERO* mirrors (Figure 4.)

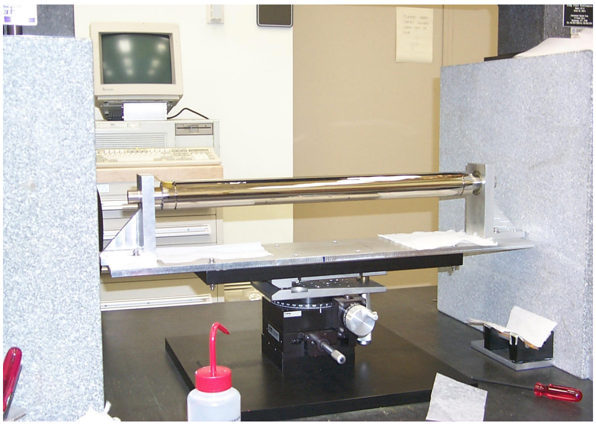


Figure 2: *HERO* mandrel on the MSFC long-trace profilometer.

Figure 3: *HERO* optic separation fixture.

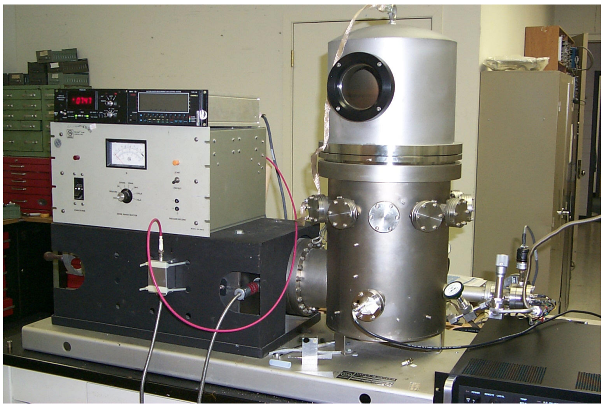
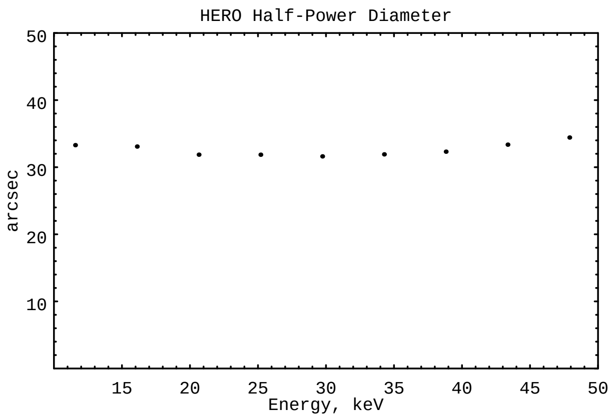


Figure 4: Iridium coating system.

Figure 5: *HERO* mirror shell and housing.

3.2 Mirror Test Results

We have recently tested our first uncoated ‘flight-grade’ mirror (Figure 5) in the 100-m test facility at MSFC. The shell was the innermost unit, 50-mm diameter and of focal length 6 m, and considered the most difficult to fabricate because of its small diameter and tendency to bow under figuring and polishing. The metrology-derived performance prediction for this optic, based on the mandrel’s axial figure, circularity, and surface roughness, indicated a half-power diameter of 28 arc sec at 60 keV.



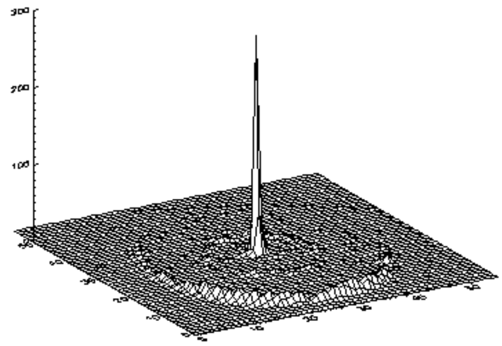


Figure 6: Half-power diameter versus energy for the *HERO* test optic.

Figure 7: Surface contour plot of mirror response over the energy range 25-35 keV taken with the GSPC.

Figures 6 and 7 show the results of our tests, for which we used a combination of a scanned pinhole -equipped CdZnTe detector and a prototype GSPC be ing developed as the *HERO* focal plane detector. The data can be seen to agree very well with the performance prediction up to the cut -off energy of 45 keV set by the finite source distance and the mirror's uncoated nickel surface. The implication of this i s that the mirror is a faithful replication of the mandrel with no additional figure distortions introduced by the shell fabrication process.

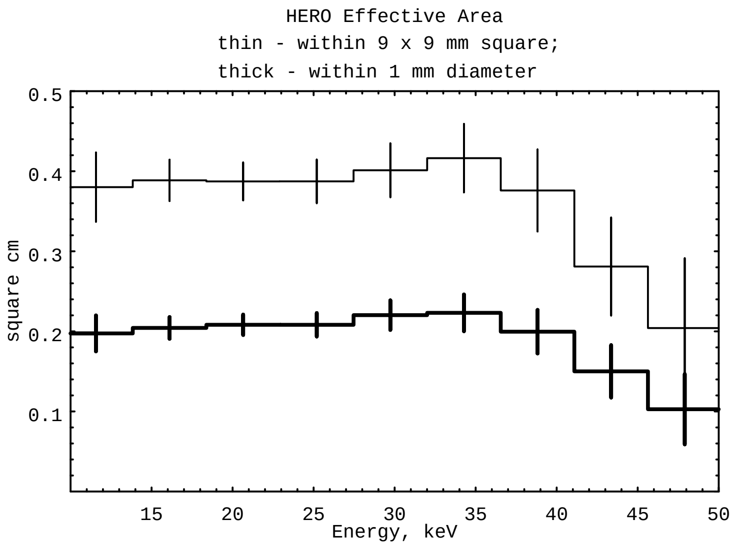


Figure 8: Effective area versus energy for the *HERO* test optic.

Figure 8 shows the measured effective area of the test optic as a function of energy. The on -axis geometric area of this particular shell is 0.5 cm^2, but the finite source distance (just over 100 m) gives a net reduction to around 0.4 cm^2. Thus the measured 0.2 cm^2 effective area within a 1 -mm diameter circle is consistent with the half power diameter measured above. As noted before, the cut -off at 45 keV is due to the finite source distance and uncoated mirror surface. When coated with iridium, this particular shell will have full response up to the iridium K edge (76 keV) for a source at infinity.

4. SCHEDULE

We currently have 6 mandrels in various stages of completion. Four of these are 6-m focal length, and two are special 3-m prescriptions that we are developing for a proving flight this fall before the gondola is modified for the longer-focal-length optics. Our schedule, pending approval for the next NASA SR&T cycle, calls for the full payload of 16 modules to be ready for flight in the Spring of 2002. However, we plan earlier flights of partial payloads, commencing with the up-coming 3-m-focal-length-optic demonstrator flight where we will check out the newly-designed gondola pointing and aspect determination systems as well as resolve issues concerning the optics alignment and the stability of optical bench designs.

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